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INVESTIGATION OF PERFORATED PLASTIC SPHERES CONCEPT FOR FUEL TANK FIRE SUPPRESSION

B. P. BOTTERI

G. W. GANDEE

Air Force Aero Propulsion Laboratory

E. J. MORRISEY

Air Force Materials Laboratory

TECHNICAL REPORT AFAPL-TR-69-1

APRIL 1969

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FOREWORD

This report summarizes the results of a technical program on the development and feasibility determination of the Whiffle Ball (perforated hollow sphere) concept for the suppression of fires and explosions in aircraft fuel tanks. The program, funded by the Limited War Office (ASJ) of the Aeronautical Systems Division under Project 1559, Task 191, was a joint effort between the Air Force Materials Laboratory and the Air Force Aero Propulsion Laboratory, with the latter organization providing overall program management.

The program required the use of both in-house and contractual efforts. In-house effort included establishing compatibility between candidate perforated spheres and the fuel and fuel system, which was performed under the direction of Mr. G. W. Gandee of the Air Force Aero Propulsion Laboratory. Contract AF33(615)-68-C-1405 with Monsanto Research Corporation, directed by Mr. E. J. Morrisey of the Air Force Materials Laboratory, provided for the production of test quantities of the candidate sphere configurations and a preliminary analysis of possible manufacturing techniques improvements. Contract D033(615)-66-5005 with the Bureau of Mines, Explosives Research Center, Pittsburgh, Pennsylvania, directed by Mr. B. P. Botteri of the Air Force Aero Propulsion Laboratory, provided for establishing the explosion suppression performance of the candidate configurations.

This report covers research conducted during the period August 1967 through 15 October 1968. The report was submitted by the authors in January 1969.

This technical report has been reviewed and is approved.

Charles R. Hudson

CHARLES R. HUDSON, Chief
Fuel, Lubrication, and Hazards Division
Air Force Aero Propulsion Laboratory

ABSTRACT

An investigation was conducted to establish the feasibility of using perforated hollow plastic spheres to pack aircraft fuel tanks to provide fire and explosion suppression capability. The program involved establishing several sphere configurations, producing test quantities, determining performance under electrical spark and incendiary gunfire conditions, and evaluating fuel system compatibility. Three sphere configurations varying in diameter from 3/4 to 1 inch with perforations of 0.060 to 0.100 mils were evaluated. All configurations provided some explosion suppression, but the goal of 3 psi maximum peak pressure rise required for fuel tank applications was not achieved. Fuel system compatibility was slightly inferior to that experienced with polyurethane foam. Spheres with optimum physical characteristics were not produced due to program restrictions. Studies indicated several potential production methods, although further development would be required.

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SECTION I

INTRODUCTION

The aircraft combat losses experienced in SEA have shown a vital need for active and passive defense measures to reduce aircraft vulnerability to the prevalent small arms threat. One of the aircraft's most vulnerable areas is the fuel tankage; therefore, the Air Force Aero Propulsion Laboratory is actively investigating advanced techniques which offer potential for reducing the threat from fire and explosion by gunfire hitting the fuel tank. Past efforts have led to the use of reticulated polyurethane foam in fuel tanks as an in-place flame arrestor to eliminate the vapor space explosion hazard, and this approach has been applied to some of the aircraft in SEA (References 1, 2, and 3).

In early 1967, a concept for suppressing fuel tank fires and explosions was evolved which, in essence, represents a second generation approach to the reticulated foam. The concept involves the use of perforated hollow plastic spheres to completely fill the tank and provide a flame arrest capability by absorbing thermal energy from the flame reaction and thereby quenching the reaction. Testing of this concept was initiated in August 1967 by the combined in-house facilities of the Air Force Aero Propulsion Laboratory and the Air Force Flight Dynamics Laboratory. The first spheres investigated were standard commercial practice plastic golf ("Whiffle") balls. These spheres had an OD of 1-3/4 inches with 13 perforations approximately 0.20 inch in diameter.

As anticipated, these spheres did not provide any vapor-phase explosion suppression. Their large diameter and the large perforations in the shell provided a total surface area that was not adequate for quenching the flames since they could propagate through the perforations.

These spheres were also subjected to liquid-phase incendiary gunfire hits in a standard tank configuration designed by the Air Force Aero Propulsion Laboratory in consultation with the Army Ballistic Research Laboratory. This test assembly employed a striker plate of 0.090 inch thickness positioned at an oblique angle of 60° to assure a 95% probability that the .50 calibre armor

piercing incendiary would function in the three-inch spacing between the striker and the test tank. With this arrangement, external fires occurred in approximately 74% of the more than 100 tests conducted with JP-4 fuel. When the standard commercial Whiffle balls were used, ignition occurred in less than 20% of the tests (3 of 16 tests). It is theorized that the spheres in the liquid act as a check valve and delay the initial spurt of fuel from the tank sufficiently long to allow incendiary burn-out.

Based on the performance of the Whiffle balls in liquid fuel, approval was obtained to pursue a program under Limited War Project 1559, Task 191, in January 1968 to establish the feasibility of the perforated hollow plastic sphere approach for aircraft fuel tank fire and explosion protection.

SECTION II

TECHNICAL PROGRAM OBJECTIVES AND PLAN

1. PROGRAM OBJECTIVES

The principal objectives of the program initiated under Project 1559-Task 191 were to develop and demonstrate the feasibility of using appropriately configured perforated hollow spheres to suppress the explosion hazard in the fuel tank ullage space and to minimize the probability of fire being started by incendiary gunfire entering liquid JP-4 fuel. The specific performance goals were similar to those associated with polyurethane foam, except that the spheres were expected to provide the additional benefit of protecting the liquid fuel. Specific performance goals were:

a. With a fuel tank randomly packed full, to limit the maximum pressure increase associated with the ignition of a stoichiometric hydrocarbon-air mixture at 0 psig initially to less than 3 psi.

b. To provide a system weight penalty 2.0 lbs/ft^3 and a fuel displacement and retention $\leq$ 4.5 volume percent.

c. To be manufactured from materials compatible with turbine fuels, such as JP-4, JP-5, commercial kerosene - JET A, and AvGas, and to be operable at temperatures ranging from -65° to +180°F.

d. To allow fuel drainage comparable to that for foam under dynamic conditions.

e. To delay the initial fuel spurt occurring when a fuel tank is ruptured by a small arms projectile, up to and including 0.50 calibre API, for a period $\geq$ 30 milliseconds.

Manufacturing technology for mass production of the spheres should be within the present state-of-the-art. If the perforated sphere approach were to prove technically feasible from the flame suppression and system application viewpoints, then costs for acquisition, installation, and maintenance should be competitive with or superior to those for foam.

2. PROGRAM PLAN

The major technical obstacle to be overcome was the design of perforated hollow plastic spheres capable of suppressing the propagation of gas-phase hydrocarborn-air flames in a manner similar to that provided by 10 ppi reticulated polyurethane foam. Considerable information was available on flame arrestors such as metal gauze, tube bundles, and open-cell polyurethane foam; however, this data provided only qualitative guidance on the design of an arrestor configuration in which the bed is packed with perforated hollow plastic spheres. Accordingly, a certain degree of flexibility had to be incorporated in the overall conduct of the program to permit the evaluation of several arrestor designs.

Unfortunately, industry had no capability for producing perforated spheres such as were needed for this program. Several sphere configurations were needed, and means of producing test quantities (to fill a fuel tank as large as 300 gallon capacity) of each sphere design were required within the resources allocated. The Air Force Materials Laboratory directed the manufacturing technology of the program. Design definition and performance testing of candidate spheres were directed by the Air Force Aero Propulsion Laboratory.

Specific elements of the program, as finally implemented, were as follows:

a. Manufacturing Technology. This portion of the program included (1) developing an effective method for producing within 5 months up to three different configurations of perforated hollow plastic spheres in quantities for up to 300 gallons of tankage; (2) selecting a suitable construction material; and (3) conducting a preliminary analysis for improving mass production techniques and evaluating costs for in-fleet aircraft application in the event the concept proved feasible. This portion of the program was conducted by the Air Force Materials Laboratory through a contract with the Monsanto Research Corporation, Dayton, Ohio.

b. Fire and Explosion Suppression Performance. This part of the program was divided into two phases: (1) in-house effort using nonperforated plastic spheres of various sizes to establish the effect of sphere diameter on flame suppression performance and provide a basis for selecting the first

perforated hollow plastic sphere configuration; and (2) contractual effort by the Explosives Research Center of the Bureau of Mines to assess the explosion suppression performance of the candidate sphere configurations. The protection provided by the perforated sphere configurations in liquid fuel was determined in tests conducted at Wright-Patterson Air Force Base.

c. Systems Analysis. This phase of the program involved investigating the performance of the candidate sphere configurations under aircraft conditions and to define associated system penalties.

SECTION III

MANUFACTURING TECHNOLOGY

The major effort in this phase of the project was to determine the best way to produce perforated hollow spheres so that a quantity could be fabricated to a particular specification at reasonable cost and to be available within 8 weeks following the initiation of the program. In addition, means had to be provided for varying the spheres as to size and perforation diameter. The 8-week time period did not permit taking more than one approach to the problem, so this approach had to provide a more than reasonable probability of success. The approach selected was to form hollow spheres and then perforate them.

1. SELECTING THE FABRICATION TECHNIQUE

The initial effort was to determine the feasibility of producing hollow spheres that were one inch in diameter with a wall thickness of about 0.01 inch, produce a pilot lot, and tool up to produce a 600-gallon quantity. These spheres were to be divided into two groups and the groups perforated with 34 holes of two different sizes. Then a 300-gallon quantity of 3/4-inch spheres was to be produced and perforated. Four fabrication techniques were considered: thermoforming, blow molding, injection molding, and a technique known as trap-thermoforming.

a. Thermoforming

In thermoforming, hemispheres having a radius of 1/2-inch and a wall thickness of approximately 10 mils could readily be formed. This technique looked promising since time and cost of die construction could be held to a reasonable level. Forming spheres by this technique, however, would require some technique for bonding the hemispheres together. Available bonding techniques included spin welding, solvent welding, and heat sealing, but none of these was considered sufficiently reliable for sealing these rather fragile hemispheres together. Therefore, this approach was eliminated.

b. Blow Molding

Blow molding could be used for constructing spheres, but reports indicated that walls could not be made sufficiently thin and the thickness is not

uniform. For example, wall thickness for a blow-molded ball 1 inch in diameter was quoted to vary from 10 to 45 mils. This approach, therefore, was also rejected.

c. Injection Molding

Injection molding was also considered, but tooling times ranged from 6 to 8 weeks, which would have provided initial delivery 1-1/2 months past the allowable delivery date. This approach, therefore, had to be rejected. This technique, however, offers the advantages of permitting precise perforations of the hemispheres during forming and providing walls of more uniform thickness. This approach was investigated later in the project.

d. Trap Forming

Trap forming and then perforating was the approach chosen for producing the spheres. This technique is basically the same as thermoforming a sheet material, except that two sheets are brought into two vacuum dies (i.e., a top and a bottom) with one of the dies designed to close on the other. The process consists of: (1) heating the two plastic sheets; (2) bringing them through the die, where two hemispheres are vacuum-formed by using a slight pressure; and (3) closing the two vacuum-formed hemispheres upon each other to form a heat seal between them. The parts are then trimmed from the sheet.

2. SELECTING THE PERFORATING TECHNIQUE

Techniques considered for perforating the spheres included mechanical punching, solubilizing of integral film layers, and thermopunching.

a. Mechanical Punching

Mechanical punching was rejected as the perforation technique because the spheres were too fragile in relation to the impact resistance of the high-density polyethylene. Furthermore, mechanical punching would produce small discs and particles that would remain within the ball and hinder fuel flow in the system.

b. Soluble Integral Film

This approach consisted of using a sheet of unperforated water-soluble film between two sheets of perforated polyethylene film. The

unperforated film would enable the perforated polyethlyene film to be formed into spheres by the trap-forming process. After the spheres were formed, they could be immersed in water and the water-soluble film washed away to open the perforations. While this approach was interesting, it was far from being practical as a method within the required delivery schedule.

c. Thermopunching

Thermopunching was the approach chosen for perforating the hollow spheres. Various techniques were considered for thermopunching, including pinpoint infrared heat, laser beams, and hot soldering gun tips. The concentrated infrared and the laser beam approaches would have required a costly equipment installation. Perforating the hollow spheres by means of hot soldering iron tips, however, proved feasible and was used. The major disadvantage of this technique was that the material melted away to form the hole remained in the sphere, thus not decreasing its weight. For the particular configuration of interest, the melted material would represent about 8 - 9% of the weight of the spheres. In practice, however, high temperatures caused a portion of the material to vaporize which helped to decrease the weight.

3. PRODUCTION OF PERFORATED HOLLOW SPHERES

Generally, the production of all three designs of perforated spheres was deficient in that the size of the holes was not uniform and the opening was often obstructed. The size of the hole depended on its location -- whether it was near a pole or the equator. Obstruction of the opening would result, apparently, from incomplete burnout of the polyethylene. These problems were due to variations in wall thickness. Orientating the spheres by hand and setting the tip dwell time to correspond with the particular thickness of the wall produced open holes of uniform size. A special handling technique could be developed for future use, but because of costs in time and money the current program could not support this development.

After the test quantities of the spheres had been produced, two alternate approaches to sphere production were evaluated. A 25-cavity rotational mold was built and attempts were made to mold high-density polyethylene into 3/4-inch diameter spheres with a 10-mil wall. Wall thicknesses between 10 and 15 mils varied considerably. Reasonable uniformity was obtained at a

20-mil thickness;however, such spheres would increase the weight penalty in aircraft systems. Therefore, this approach, was abandoned.

The second approach was a snap-fit design for injection molding 10-mil-wall hemispheres. The undercut provided by a 10-mil-wall section was not sufficient for a reliable snap-action assembly. The mold was modified, therefore, to provide for perforating the hemispheres and providing an extra wide flange at the equator for heat sealing. Although the spherical shape was somewhat distorted when the perforated hemispheres were removed from the mold, this method produced perforated spheres of uniform size with clear holes.

4. FUTURE SPHERE PRODUCTION

Subsequent to this development, a facility has been found that produces golf whiffle balls with uniform wall thicknesses and circular holes. A three-step procedure is used; (a) hemispheres with uniform walls are injection-molded; (b) circular holes are mechanically punched in the hemispheres; and (c) the two hemispheres are heat-bonded at the equator. The heat-bonding appears to be the rate-limiting step; 4 balls (8 hemispheres) can be heat-bonded on an 8-second cycle. This heat-bonding equipment can be modified, however, to handle 8 spheres per cycle. Since this method is being used to produce golf whiffle balls, it is anticipated that the manufacturer could produce perforated spheres to Air Force specifications on a fixed-price basis. This three-step procedure overcomes the distortion that occurred in molding and heat-sealing perforated hemispheres with circular holes.

SECTION IV

THE VULNERABILITY PROBLEM AND SUPPRESSION MECHANISMS

1. VULNERABILITY OF AIRCRAFT FUEL TANKS

The vulnerability of aircraft fuel tanks to gunfire can be depicted by considering incendiary projectiles. These projectiles can ignite the fuel when they impact in either the liquid or ullage space of fuel tanks. The mechanisms for ignition in the liquid space is depicted in Figure 1. Fuel tanks are positioned in aircraft so that a void space exists between the aircraft skin and the fuel tank wall. As the incendiary penetrates the aircraft skin, it deposits its burning particles in the void space. The temperature of these incendiary particles may be greater than 4000°F, and the burn time for a .50 calibre projectile, for example, averages about 30 msec. As the projectile passes through the liquid fuel, the fluid pressure increases, which results in the fuel back-spraying through the hole the projectile made in entering the fuel cell and into the void space. The fuel spray coming in contact with the burning incendiary particles results in a fuel fire.

When an incendiary projectile, tracer, or high-energy fragment penetrates the ullage of an aircraft fuel tank, the principal hazard is explosion because of the confined conditions. Under confined conditions, combustion of hydrocarbon fuel-air mixtures can cause a pressure rise approximately seven times the initial ambient pressure of the mixture; maximum pressure rise occurs with near stoichiometric fuel vapor-air mixtures. As fuel-air mixtures deviate from stoichiometric, either toward lean or rich flammability limits, peak pressures are reduced. The time required to reach the maximum pressure after ignition is influenced by the fuel/air ratio, initial mixture pressure, temperature, and tank volume. For typical aircraft fuel tanks with a stoichiometric fuel-air mixture at 0 psig, this time interval is approximately 70 milliseconds; the pressure-time profile indicates that a period of approximately 50 milliseconds elapses before the pressure increases by 5 psi, but in the next 20 milliseconds, the pressure increases very rapidly (about 85 psi). Pressure increases in excess of 3 psi can result in fuel cells

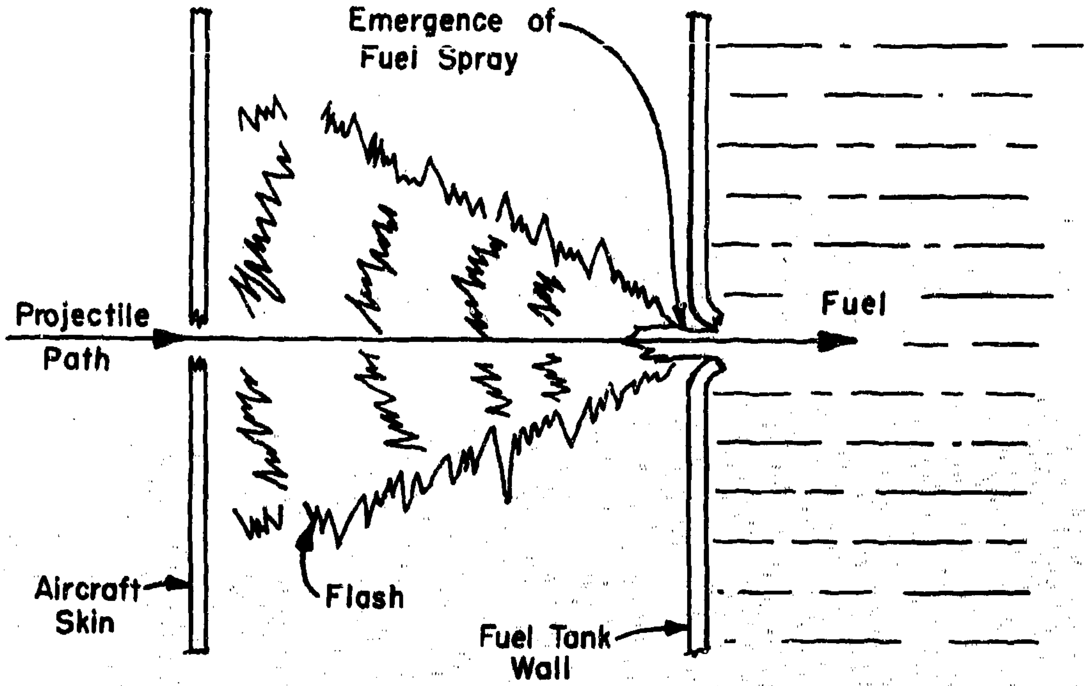

Figure 1. Mechanisms of Ignition by Incendiary Projectile

rupturing and damaging the aircraft structure. Fire and explosion suppression techniques must be capable of not only counteracting the explosion threat, but of limiting the pressure increase to less than 3 psi.

2. FIRE AND EXPLOSION SUPPRESSION MECHANISMS

Sustaining the combustion process requires that the fuel, oxidizer, and energy sufficient to maintain the chemical reactions be continually resupplied. The reactions occurring in the gas phase also involves the formation, consumption, and regeneration of free radicals, which are intimately involved and are essential to the overall combustion process. Suppressing the combustion involves the use of physico-chemical actions capable of counteracting one or more of these combustion elements. The basic modes of suppression are as follows:

a. Separation of Fuel from Oxidizer. This is the principal mode of extinguishment provided by fire fighting foams and is commonly referred to as "blanketing."

b. Dilution of Fuel or Oxidizer. When the concentration level of either the fuel or the oxidizer is diluted sufficiently, the mixture will be incapable of supporting the combustion reaction. Nitrogen inerting systems function by this mechanism.

c. Absorption of Energy. Rapid absorption of the combustion energy results in the overall cooling or quenching of the reaction. Water is typical of an extinguishing agent which acts effectively in this manner.

d. Chemical Action. Chemicals that interact with the free radicals, which promote the combustion reaction, include halogenated hydrocarbons containing bromine, chlorine, iodine, and alkali metal salt compounds such as sodium bicarbonate and potassium bicarbonate. These agents appear to inhibit combustion by both chemical and physical means.

In addition to using extinguishing agents such as nitrogen, water, and chemicals, there are passive techniques that can be used for fire and explosion suppression. The most common of these involves the flame arrestors such as wire gauze screens found in miners' lamps, tube bundle arrays used in aircraft fuel tank vents, and reticulated polyurethane currently being used for packing fuel tanks. These arrestors function by quenching or cooling, which is the mechanism employed in the polyethylene spheres arrestor concept discussed here.

When a flammable fuel-air mixture ignites in the ullage of a fuel tank, the flame front propagates from the point of ignition in all directions into the unreacted fuel-air mixture. Propagation of the flame is contingent on sufficient energy being transferred from the reaction front to the unreacted fuel-air mixture. Flame arrestors such as wire gauze screens, tube bundles, and open-cell polyurethane foam generally suppress flame propagation by absorbing thermal energy from the propagating flame and thereby preventing the adjacent fuel-air layer from igniting. Energy absorption must be sufficient to reduce the flame temperature in the reaction zone below the level of the lean-limit fuel-air flame temperature ($\sim 1700°$ K for hydrocarbon fuel-air mixtures).

The design of a flame arrestor must consider the combustion properties of the fuel oxidant combination, the environmental parameters such as the initial temperature and pressure of the mixture, and the geometric parameters of the confining structure, all of which influence the flame impingement velocity, the thermal energy release, and the associated pressure increase. The inherent performance of an arrestor is dependent upon the thermal conductivity and specific heat properties of the material used in its construction and its geometric configuration in terms of the amount of surface area available for cooling.

Depending upon the above considerations, satisfactory arrestor performance, in certain cases, must be achieved by providing greater arrestor depth for effective quenching. Low specific heat and thermal conductivity materials such as open-cell polyurethane foam exhibit poorer arrestor performance than metal gauze screens; polyurethane foam achieves acceptable performance by means of greater arrestor depth; thus, the flame front must penetrate some distance into the foam before it is quenched. At pressures above 10 psig, however, the 10 ppi reticulated polyurethane foam, even in a fully packed tank, becomes ineffective.

SECTION V

PLASTIC SPHERE CONFIGURATION TESTS

1. DETERMINING CANDIDATE CONFIGURATIONS

To establish the sphere diameter required for effectively suppressing flame propagation through the interstitial voids of a randomly packed configuration, the Air Force Aero Propulsion Laboratory conducted a heat transfer analysis and experimental explosion suppression tests with solid shell spheres of various diameters. Tests were conducted in a combustion chamber measuring 1 foot in diameter and 2 feet long. The spheres were packed in a wire-mesh cage designed to fit tightly in the chamber. The length of the arrestor was less than 2 feet to provide a void space at the ignition end, thereby permitting a limited distance for flame runup to enhance its propagation velocity. In some of the tests, a void space was also provided at the downstream end of the arrestor. Instrumentation in the chamber was designed to provide combustion reaction pressure profiles and flame propagation velocities from the ignition void to the downstream void. A window at the downstream end of the chamber permitted any flame penetration through the arrestor to be observed. All tests were conducted with near stoichiometric propane-air mixtures at 0 psig and approximately 70° F to ensure that the arrestor was subjected to the most severe velocity and pressure increase conditions. Results of these tests are plotted in Figure 2.

Figure 2 indicates that to suppress flame propagation (pressure rise < 3 psi) through the interstitial void spaces, the spheres cannot be larger than 1 inch in diameter. Perforated hollow plastic spheres were not available for testing, so data on quenching distance for hydrocarbon-air mixtures was used to establish the diameter of the perforations. A perforation diameter of 0.100 inch was selected for the first candidate configuration.

The next problem was to analyze the effects of sphere diameter, shell thickness, and number of perforations on the weight and fuel displacement. The effects of the above variables were calculated using a random packing factor of 0.65 and spheres constructed of high-density polyethylene (density of 0.97 gm/cc). The results of these calculations are plotted in Figures 3 through 6.

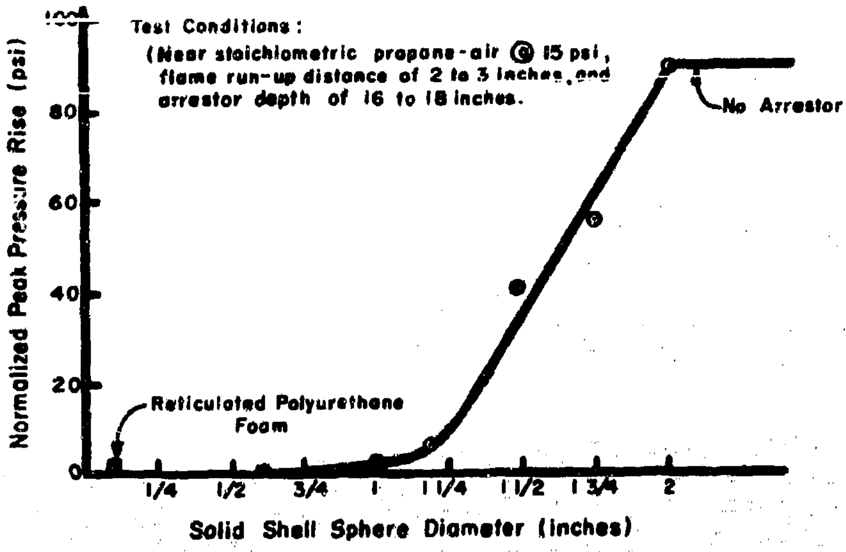

Figure 2. Explosion Suppression Performance of Solid Shell Plastic Spheres

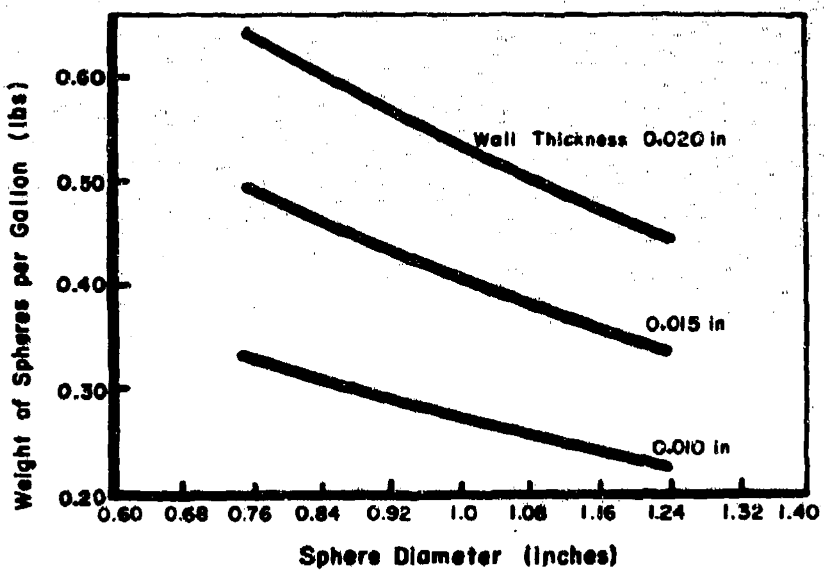

Figure 3. Weight of Spheres as a Function of Sphere Diameter and Wall Thickness

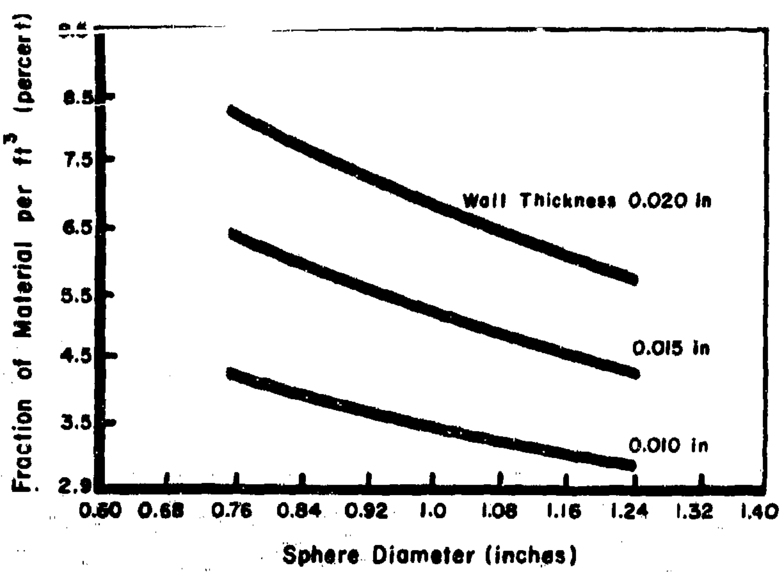

Figure 4. Sphere Material as a Function of Sphere Diameter and Wall Thickness

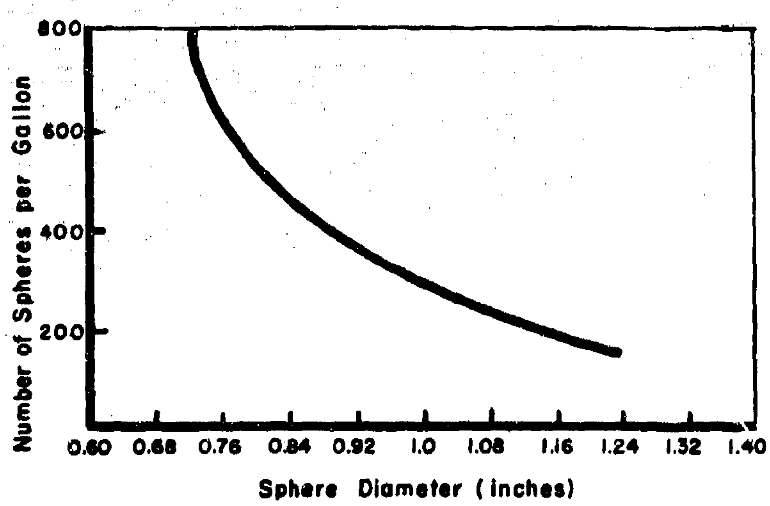

Figure 5. Number of Spheres as a Function of Sphere Diameter

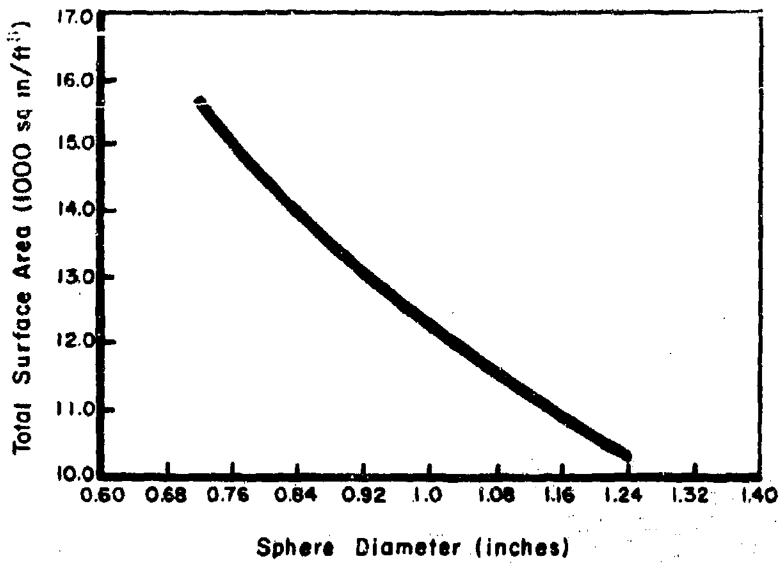

Figure 6. Total Sphere Surface Area as a Function of Sphere Diameter

With a maximum allowable sphere diameter of 1 inch, Figures 3 - 6 indicate that achieving a weight penalty of 0.3 lbs/gal and a fuel penalty of 4.5 volume percent (allowing 1 volume percent for fuel retention) would require a wall thickness of approximately 0.010 inch.

The number of perforations in each sphere was established in a qualitative manner with the emphasis on the uniformity of their distribution. The objective was to limit the amount of fuel retained in the sphere while maintaining sufficient spacing so as not to weaken the shell.

Economic factors permitted only three configurations to be considered for test quantity production; two had the same overall dimensions but different size perforations, and the third had both a different diameter and perforation. These spheres were designated as Configurations A, B, and C, with B and C to be finalized as test results were obtained from Configration A. The final designs of these configurations are defined as follows:

Configuration A - Hollow, high-density polyethylene spheres measuring 1 inch in diameter having a nominal wall thickness of 0.010 inch, and 34 uniformly spaced perforations measuring 0.10 inch in diameter.

Configuration B - Hollow, high-density polyethylene spheres measuring 1 inch in diameter with a nominal wall thickness of 0.010 inch and 34 uniformly spaced perforations 0.060 inch in diameter.

Configuration C - Hollow, high-density polyethylene spheres measuring 3/4 inch in diameter with a nominal wall thickness of 0.010 inch and 34 uniformly spaced perforations 0.090 ± 0.010 inch in diameter.

2. INITIAL TESTS OF SPHERE PERFORMANCE

The performance of the sphere configurations in suppressing flames was evaluated by the Bureau of Mines. An electric spark and incendiary gunfire were used as the ignition sources. Most of the investigation was performed in laboratory-scale combustion chambers instrumented with pressure transducers and fast response thermocouples. These chambers included a cylindrical vessel measuring 6 by 60 inches and a Pyrex vessel measuring 12 by 60 inches, shown in Figures 7 and 8. A 27 by 30 inch center section of an F-105 external fuel tank (Figure 9) was used for the gas-phase explosion suppression tests. All tests were conducted with near stoichiometric mixtures of butane-air or n-pentane-air; a stoichiometric mixture ensured that the system was being subjected to the most severe combustion reaction conditions.

Several packing factors were used, from 0.65 to 0.70, which approaches the maximum (0.74). Packing factors greater than 0.65 required manual placement of individual spheres. The influence of initial fuel-air pressure and temperature was also investigated. The 10 ppi reticulated polyurethane foam was also used to provide comparative performance data under identical test conditions.

3. LABORATORY COMBUSTION CHAMBER TESTS

The pressure rise versus initial pressure of the fuel-air mixture from experiments conducted in a fully packed tank section (12 x 35 inches) with 10 ppi polyurethane foam and with randomly packed polyethylene spheres (~65-68% packing density) is shown in Figure 10. The fuel, ~2.5% n-pentane and air mixture, was used in this test series. Data obtained in these tests indicates that, at the 0 psig initial pressure condition, Configurations A, B,

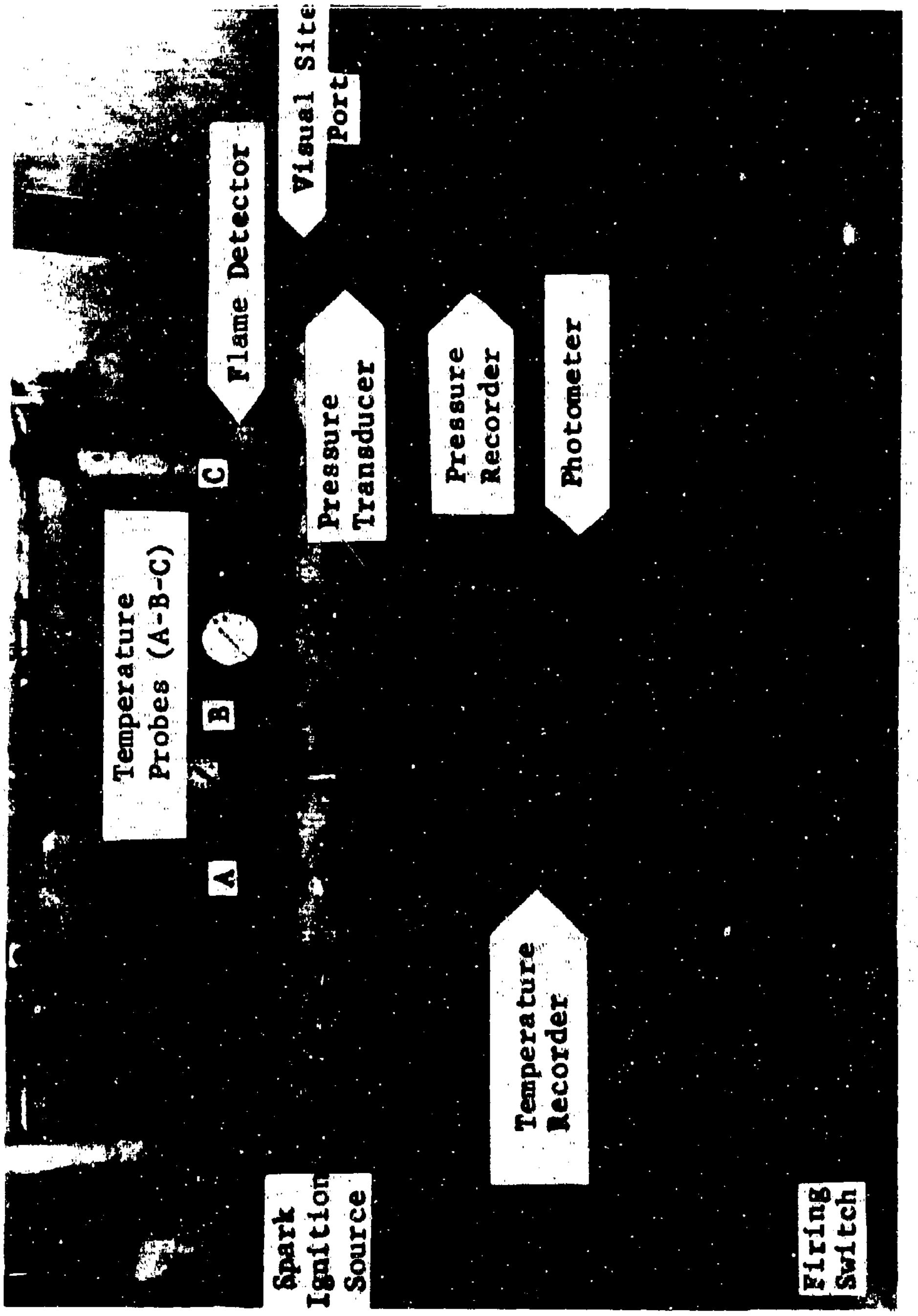

Figure 7. Experimental Setup for Flame Arrestor Experiments Showing 6 x 60 Inch Chamber and Instrumentations

Figure 8. Pyrex Chamber Packed with Spheres

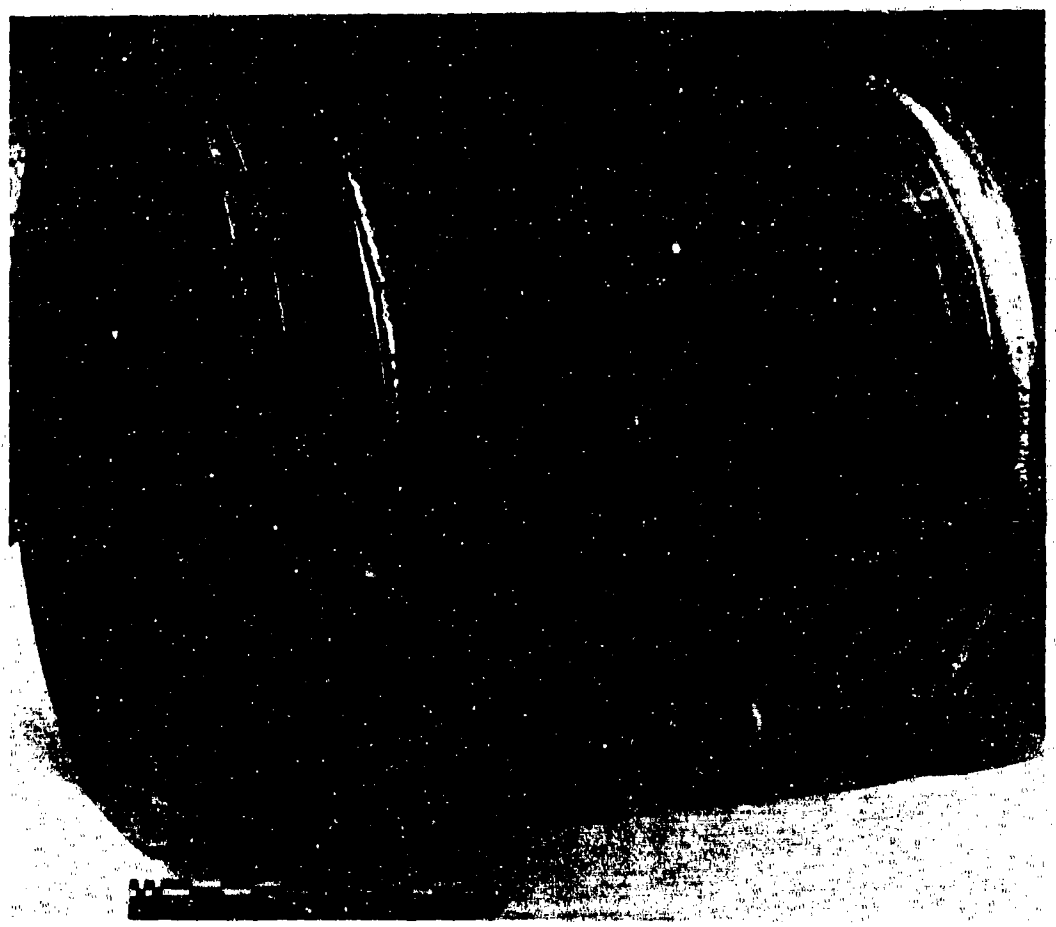

Figure 9. Section of F-105 Fuel Tank Used in Flame Arrestor Experiments

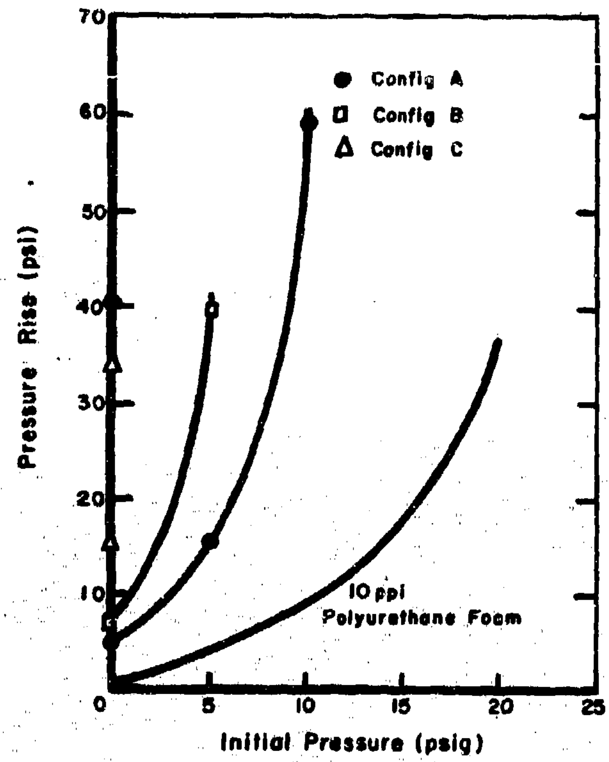

Figure 10. Pressure Rise Vs. Initial Pressure for Various Flame Arrestors in a Fully Packed Vessel

and C all provided considerable flame suppression capability, but Configuration A was superior. The performance of all three configurations was inferior, however, to that of 10 ppi polyurethane foam. The performance of a particular configuration was not consistent from test to test. For example, Configuration A in 12 of the test runs yielded a peak pressure increase of ~ 6 psi while in 3 the peak pressure was as high as 40 psi. This discrepancy in performance was attributed to natural variations in packing arrangement.

As the initial pressure is increased above 0 psig, the performance of the spheres degraded rapidly. More important, at the 0 psig condition, none of the sphere configurations achieved the performance goal of 3 psi maximum pressure rise required for aircraft fuel tank applications. By comparison, the 10 ppi polyurethane foam provides acceptable performance under these test conditions at initial pressures up to 5 psig.

Based on the solid-sphere experiments (discussed earlier), the flame suppression performance of Configuration C was expected to be superior to that of either A or B. Test results depicted in Figure 10, however, clearly indicate inferior performance. Tests conducted in the glass flame tube and photographed with high speed cameras indicated that the Configuration C spheres, because of their lighter weight, are much more easily displaced by the propagating flame front than are either A or B. Such displacement permits greater flame penetration prior to quenching, with a constant higher peak pressure rise. In addition, Configuration C spheres exhibit greater nonuniformity in random packing. When the packing density was increased from 65 to 70%, however, performance of Configuration C was comparable to that of Configurations A and B.

Figure 11 provides typical pressure rise versus time profiles from experiments conducted in a fully packed vessel with 10 ppi polyurethane foam and in randomly packed (65%) Configuration A, B, and C spheres. A near stoichiometric ($\sim$ 2.5 volume %) n-pentane-air mixture was used; for an initial 0 psig mixture pressure, peak combustion pressures would be approximately 100 psi. The pressure-time profiles indicate the perforated sphere arrestors provided considerable attenuation, but the performance of the 10 ppi foam is clearly superior.

4. GUNFIRE TESTS

Performance of the perforated plastic spheres was also evaluated in suppressing fire and explosions from incendiary projectiles entering the liquid and ullage space of fuel tanks. These tests used JP-4 fuel and were conducted in the standard test tank. Tests in which the incendiary projectile entered the liquid were conducted with Configuration A, which had exhibited the best explosion suppression capability in the Bureau of Mines evaluation. Ignition occurred in all these tests, which indicates no reduction in vulnerability. In earlier tests with the larger whiffle golf balls, the probability of ignition had been reduced to less than 20%; the loss of this protection benefit is attributed to the small size of the Configuration A spheres. A tumbled 50-caliber incendiary penetrating through the tank wall forms a hole approximately 1-1/2 inch in diameter. To act effectively as check-valves, apparently, the spheres must be of comparable size. Effective gas-phase explosion suppression,

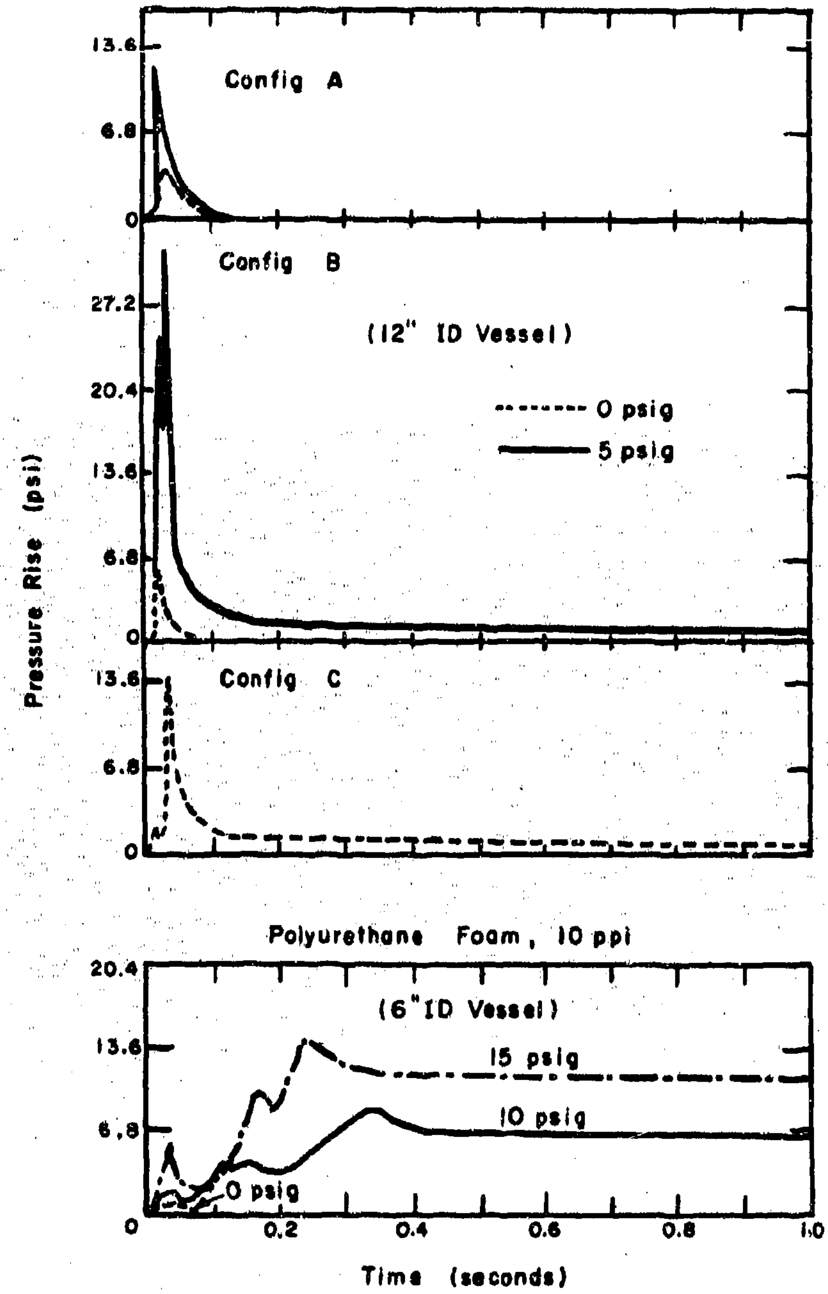

Figure 11. Pressure Rise Vs. Time for Various Flame Arrestors in a Fully Packed Vessel

however, dictated the use of smaller spheres to provide sufficient surface area and limited interstitial void space. Thus, using a single perforated hollow plastic sphere to provide adequate fire protection benefits for both liquid and vaporous fuel does not appear to be attainable.

Explosion suppression testing of Configurations A, B, and C in which incendiary gunfire entered the ullage space of the fuel tank was conducted by the Bureau of Mines. The center section of a 450-gallon F-105 external wing tank was equipped with pressure transducers and thermocouples. A near stoichiometric n-butane-air mixture at 0 psig was used. The ignition source was a 30-caliber incendiary projectile. The test cell was fully packed (~ 65% packing density) with the spheres. In these tests, peak pressures were higher than those observed in the laboratory experiments, and ranged from a minimum of 12 psi for Configuration A to 20 psi for Configuration C. The higher pressures are attributed to the nature of the ignition source and its interaction with the spheres. The electric spark used in the laboratory experiments was a single point ignition source; the incendiary, however, is a multipoint ignition source that is capable of initiating combustion anywhere along its path. In addition, the projectile as it passes through the arrestor momentarily displaces the spheres and creates a temporary void space. These two factors result in a greater overall flame propagation with attendant larger peak pressure rises.

SECTION VI
SYSTEM ANALYSES

1. FUEL PENALTIES

Penalties associated with Configuration A and B spheres with both the 100- or 60-mil perforations were investigated. A 55-gallon drum was modified by removing the bottom and attaching a 1-1/4 inch outlet and valve to the 2-inch bung. This drum was secured to a frame and the entire system was mounted on a scale. In these tests, the drum with the dry spheres was weighed, then the drum with a corresponding volume of fuel was weighed, and finally the drum filled to the same level with the spheres and fuel was weighed. The system was then gravity drained with and without the spheres and the fuel weight and time was recorded.

The results of these tests are summarized in Table I. As can be noted, higher penalties were experienced than would be expected from 10-mil-wall spheres. The weight penalty was approximately 0.50 lb/gallon, and the volume displacement was approximately 6.1%; this indicates an average wall thickness for the spheres of 17 mils.

A significant quantity of air was trapped in the spheres during the fueling operation. The indicated volume displacement prior to the removal of the air ranged from 1.4 to 2.3% higher than the final value; as anticipated, Configuration B trapped more air than A. This air, which was trapped due to the random orientation of the perforations, could be readily removed by agitating the container. This trapped air, however, emphasizes the need for a maximum number of holes in the spheres; the calculated number of holes for future spheres is 43, compared to the 34 provided in production spheres for these tests.

The fuel retention due to surface wetting and fuel trapment was approximately 1.2% and did not appear to be affected by the hole size; with more holes, fuel retention may be reduced. This value is comparable to that for the foam. The gravity flow data is summarized in Table II. The results indicate that Configuration A spheres do not appreciably alter the flow rate, but

TABLE I

FUEL PENALTIES TESTS

(55-gallon drum filled within 2 1/2 inch of top, 1 1/4 inch fuel outlet, scale with 1-lb divisions)

	Specific Gravity of Fuel	Weight (lbs)		Fuel and Spheres	Drum Weight, (lbs)		Calculated Penalty (%)		Weight Penalty lbs/gal
		Spheres	Fuel		Empty	With Spheres	Displace-ment	Fuel Retention	
Configuration A	0.763	26.75	352.0	351.75	3.75	35.25	7.81[a]	1.30	0.489
Configuration B	0.764	27.9	349.75	355.0[b]	1.5	34.0	6.35	1.21	0.510
Configuration C	0.767	26.5	347.5	353.5[c]	2.0	36.0	5.83	1.16	0.487

a Air trapped in spheres not removed.

b Air removed; with air, weight was 350.25 lbs.

c Air removed; with air, weight was 345.5 lbs.

TABLE II

GRAVITY FLOW TEST RESULTS

	Tank Packed						Tank Clean		
	Configuration A			Configuration B					
Tank Condition	Wt. (lbs)	Time (sec)	Level Change (ft/min)	Wt. (lbs)	Time (sec)	Level Change (ft/min)	Wt. (lbs)	Time (sec)	Level Change (ft/min)
Full	355	0	-	353.5	0	-	349.25	0	-
3/4	273	24.5	1.68	271.0	25	1.5	262	23	1.79
1/2	191.5	52.3	1.48	189.5	52	1.44	174.5	49.6	1.55
1/4	109.5	86.5	1.21	107.5	89	1.02	87.25	81	1.31
Empty	40.5	138	0.97	36.	160	0.50	4.5	125	0.94

Configuration B causes some holdup. The drop in fuel level, which averaged about 1 1/2 fpm, is much greater than would occur in an aircraft system.

2. PUMPING CHARACTERISTICS

The flow characteristics of JP-4 fuel from a tank packed with Configuration A or B spheres were studied in four series of tests. A 100-gallon tank was equipped with a centrifugal boost pump from an F-101 aircraft having an output capacity of 31,000 lbs/hr. The first tests were run with the tank clean (no spheres) to provide a base line for the system flow characteristics with JP-4 fuel. Tests were then conducted under identical conditions with the tank packed with perforated spheres or foam. In packing the tank, a void area was left around the inlet to the pump; this void was achieved by covering the pump with an 8 mesh-screen when packing with the spheres, or cutting out some of the material when packing with foam.

The primary variable was the fuel flow rate, which ranged from 10,000 to 31,000 lbs/hr. Flow rate was recorded by a Pottermeter. The total time to pump down the system was taken as that instance when the pump began to cavitate, as indicated by a loss in pump discharge pressure and a corresponding decrease in the fuel flow. In each test, the tank was filled to a set position, the gate valve downstream of the flowmeter was set to a given position, and the fuel pumped into a 300-gallon reservoir. After the test, the fuel level was measured both in the tank and in the reservoir.

Data from these tests was used to construct Figure 12. The relative performance of the system appears to be linear over this flow range, and the flow characteristics are similar with the various fillers. The gross volume displacement of the fuel was corrected for the presence of the fillers. The resultant normalized data indicated a fuel transfer efficiency of 97% for the foam and 95% to 96% for the perforated spheres. The difference in performance may be attributed to the perforation configuration, as was noted in the gravity flow and fuel penalties tests. Following the pumping tests, the residual fuel drained down in a matter of minutes so that it could be pumped out. Configuration B, with its smaller perforations, did not alter system performance as much as might be expected.

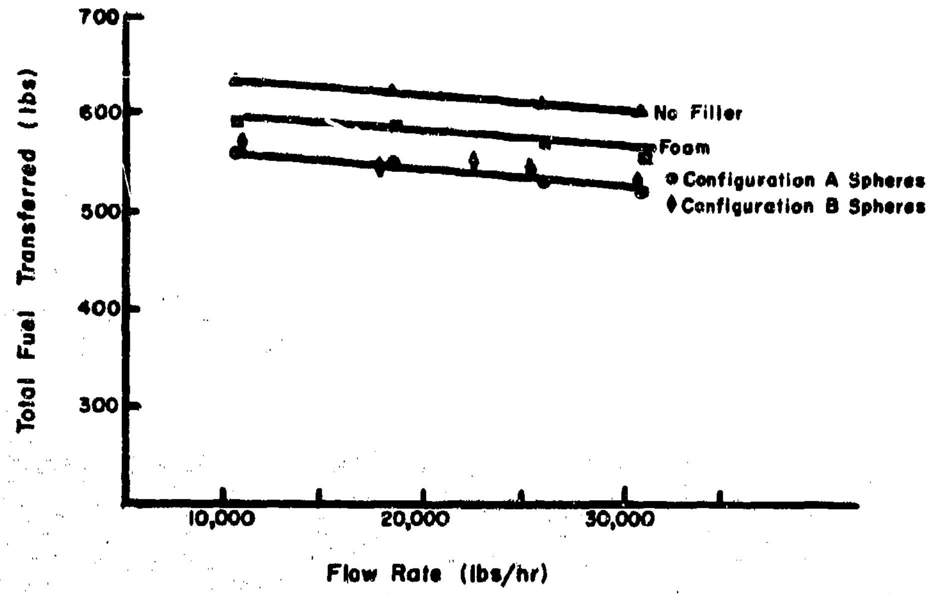

Figure 12. System Pumping Characteristics with and without Perforated Spheres

3. SLOSH AND VIBRATION TESTS

The performance of perforated spheres in an aircraft fuel tank was investigated by conducting a standard slosh and vibration test. This test, run in accordance with MIL-T-7378, subjected a fully packed tank to a total of 25 hours of simultaneous vibration and slosh testing, typical of that encountered when installed on an aircraft. Initially, the 200-gallon external tank with viewing ports (which had been used for evaluating the foam) was to have been used, which would have supplied a direct comparison between the foam and the spheres. The quantity of spheres available was limited, however, so a smaller system had to be used. Two tanks from the F-104G aircraft were substituted, which have capacities of 45 and 60 gallons. These tanks were designed for the gun bay and the ammunition compartment, respectively, and had previously been subjected to slosh and vibration tests.

The gun bay tank was firmly packed with the Configuration A spheres and the ammunition compartment tank was loosely packed with Configuration B

spheres. Each tank was filled to two-thirds of the net usable level with unfiltered JP-5 fuel. During the filling operation, fuel spilled back out the vent, indicating that the spheres were restricting the flow, which suggests that the area around the filler cap should be voided of spheres.

The tanks were mounted on the test stand and the 25 hour test was run at ambient conditions over a period of a week. Following the test, the tanks were drained, and the fuel from the sump area was analyzed for plastic particles from the spheres. The spheres were visually examined for signs of deterioration, and the tanks inspected for plastic particles.

The fluid analysis and visual inspection revealed that there was essentially no deterioration of the spheres and the plastic did not break off in areas adjacent to the perforations. The tanks were free of plastic particles. The spheres swelled, however; the 60-gallon tank, which had been loosely packed, had become firmly packed. Spheres in the 45-gallon-tank, which had been firmly packed, were not affected by the swelling. The areas where the spheres contacted the walls in both tanks were polished, indicating the spheres moved slightly during the tests.

4. SMALL-SCALE LABORATORY TESTS

To ensure that the spheres were acceptable from an environmental standpoint, a number of small-scale laboratory tests were conducted. These tests were conducted to determine (1) the effects of the spheres on fuel properties, (2) the compatibility of the spheres with various fuels, and (3) the effects of environments over the temperature range of -65°F to +180°F.

To determine the effects of the spheres on the fuel properties, the spheres were soaked in Type III test fluid for 45 days at ambient conditions and the exposed fuel was analyzed. The two components of Type III fluid, 70% iso-octane and 30% toluene, were checked before and after exposure. Results are presented in Table III. These tests indicated that the fuel extracted none of the sphere material.

TABLE III

SPHERE EXPOSURE TO TYPE III FLUID

Test	Control	After 45 days Exposure
Silting Index	0.12	0.04
Refractive Index	1.4197	1.4197

For fuel specification tests, the spheres were soaked in JP-5 fuel and selected tests run after 7 days and 30 days. Data from these tests, which are summarized in Table IV indicate that the fuel was not degraded. The JP-5 did not contain the anti-icing additive, however, so the spheres were exposed to a 50/50 mixture of anti-icing compound and water. Refractive index checks before and after the 7-day exposure were identical. Gas chromatographic analysis also indicated no fluid change.

TABLE IV

PERFORATED SPHERES SOAKED IN JP-5 FUEL

Test	Control	After Exposure	
		7 Days	30 Days
Silting Index	0.33	0.69	0.56*
Micro-Coker, Breakpoint, °F	500	475	-
Refractive Index	1.4462	-	1.4461*

*Average of two batches of spheres

The spheres from the above tests were visually inspected to determine the effects of the fluids on the spheres. The spheres appeared to be fairly stable, although they tended to swell in all the tests. For example, spheres filling a 5-gallon container were soaked overnight in JP-5 fuel. When the spheres were taken out of the container, dried, and put back in, approximately 1000 ml of spheres remained.

A more detailed study of the swell characteristics of the high density polyethylene material was carried out under contract by the Monsanto Research Corporation. (They used bar stock material in lieu of spheres to facilitate measurement.) Samples of the material were exposed to Type III test fluid conforming to TT-S-735 for periods of 7 and 30 days at temperatures ranging from 74 to 130° F.

The results of these tests, summarized in Table V, confirmed the marked tendency for the material to swell. The increase in volume ranged from 6.8 to 9.6 percent and was found to be more dependent upon temperature than time of exposure. In 7 days, for example, the volume increased 9.2% at 130° F as compared to the 6.8% at 74°F.

TABLE V

SWELL CHARACTERISTICS OF HIGH DENSITY POLYETHYLENE IN TYPE III FLUID

Specimen - 1/8 inch thick disk or bar

Fluid Temperature (°F)	Immersion Time (Days)	Volume Increase, Average (Percent)
74	7	6.8
74	30	7.0
130	7	9.2
130	30	9.6

The effect of environment was investigated by subjecting fuel-wetted and fuel-immersed spheres to the temperature extremes of -65°F and ±180°F. The spheres were cold soaked at -65°F for a period of 72 hours, then vibrated for a period of 5 minutes; some spheres were again chilled to -65°F and drop tested from a height of 6 feet. The spheres maintained their original properties and integrity. After exposure of 1 day in JP-5 fuel at 180°F, the spheres appeared to be unchanged.

The fuel from these tests was passed through a 0.45 micron filter and the filter examined for plastic particles. A few particles were found, but the spheres had not deteriorated to any degree. These plastic particles appeared to have come from material built up around the holes during the perforation process. Dry spheres tended to free more particles than fuel-wetted ones.

5. PRESSURE DROP STUDIES

Air flow characteristics through a packed section of the spheres was investigated by the Bureau of Mines. The testing was conducted in an 8 by 60 inch cylindrical steel pipe which contained a packed section of either the spheres or reticulated foam. This packed section, ranging in length from 6 to 24 inches, was held in place by a 2-mesh screen. Seven manometers were installed for recording the pressure drop. The air flow was controlled by a calibrated orifice located downstream of the test section. All testing was conducted at ambient conditions and with the pipe mounted in a vertical position.

The tests conducted with the full 24-inch section indicated that at air velocities less than 20 ft/sec the pressure drop per inch with the spheres was similar to that obtained with 20 ppi foam. At higher velocities, up to 60 ft/sec, a difference was apparent between the foam and the spheres; however, the compressive force distorted the foam but not the spheres. Thus, the pressure drop per unit length is meaningful only at air velocities less than 20 ft/sec, as shown in Figure 13. Tests with other lengths of packed area, summarized in Table VI, show the pressure drop per unit length to increase with an increase in air velocity and not to vary significantly over most of the length. Figure 14 presents the anticipated pressure drop as a function of position in the packed area with varying air flows.

TABLE VI

EFFECTS OF WETTING ON PRESSURE DROP IN PACKED VESSEL

Packing	Air Velocity (ft/sec)	ΔP (psi)
Configuration A Spheres		
Dry	5.0 9.6 19.1 22.8	0.185 0.515 1.548 2.085
Wet	5.1 9.7 19.3 22.9	0.211 0.565 1.717 2.261
10 ppi Reticulated Polyurethane Foam		
Dry	5.0 9.9 20.1 22.7 24.4	0.065 0.229 0.858 1.059 1.194
Wet	5.0 10.1 20.7 23.3	0.090 0.334 1.215 1.015
20 ppi Reticulated Polyurethane Foam		
Dry	5.0 10.0 20.5 23.2 25.0	0.120 0.409 1.482 1.851 2.122
Wet	5.0 10.1 20.9 24.8	0.121 0.486 2.171 3.032

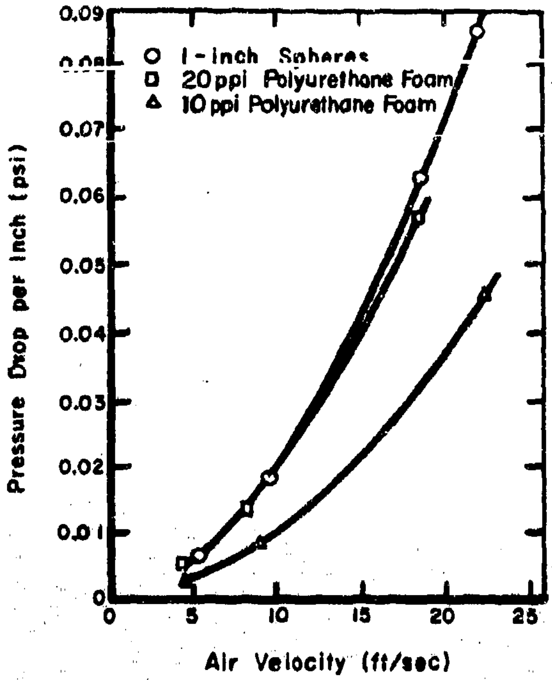

Figure 13. Pressure Differential as a Function of Flow Velocity

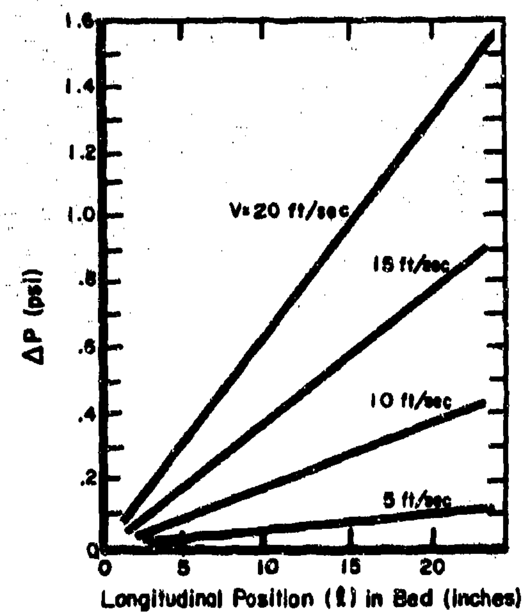

Figure 14. Pressure Drop Vs. Longitudinal Position and Air Velocity

Pressure drop measurements were also made under two different wetting conditions. In one procedure, an 8-inch cylinder packed with spheres was saturated uniformly with water. Data from these experiments, summarized in Table VII, indicates no difference in the pressure drop between the spheres and the 20 ppi foam.

TABLE VII

PRESSURE DROP AT VARIOUS AIR VELOCITIES AS A FUNCTION OF LONGITUDINAL POSITION

Longitudinal Position in Bed (inches)	ΔP, psi at Various Air Velocities			
	4.7 ft/sec	7.8 ft/sec	17.6 ft/sec	44.3 ft/sec
18-Inch Bed				
2	0.011	0.031	0.116	0.305
6	.031	.082	.329	1.267
9	.043	.113	.469	2.193
12	.052	.144	.631	3.179
18	.078	.217	.931	5.324
12-Inch Bed	3.3 ft/sec	7.1 ft/sec	17.6 ft/sec	39.7 ft/sec
2	0.008	0.027	0.133	0.418
6	.015	.065	.334	1.449
9	.020	.089	.476	2.071
12	.033	.121	.660	3.045
6-Inch Bed	7.8 ft/sec	13.6 ft/sec	28.3 ft/sec	52.6 ft/sec
2	0.034	0.089	0.340	0.968
6	.081	.217	.847	2.834

SECTION VII
CONCLUSIONS

1. Although the three candidate perforated hollow plastic sphere configurations exhibited significant flame suppression capability when randomly packed (0.65 packing factor) in a tank arrestor array, the goal of 3 psi maximum pressure increase required for aircraft fuel tank applications was not achieved.

2. Performance of all three configurations was reduced when an incendiary gunfire projectile was used instead of an electric spark as the ignition source. The inferior performance is attributable to two factors: (1) the incendiary projectile represents a multiple-point ignition source and (2) in passing through the arrestor array, the projectile creates a temporary open-path. These factors result in greater overall flame propagation and consequent higher peak reaction pressures.

3. The explosion suppression performance of the spheres was improved by increasing the packing factor close to the maximum theoretical value of 0.74. Unfortunately, a packing factor greater than 0.65 is impractical because it requires careful positioning of each sphere. For practical applications, the concept would have to be effective with random packing.

4. The perforated hollow plastic spheres were much more difficult to produce than had been anticipated, and the candidate configurations could not be produced with the desired uniformity in outer diameter, wall thickness, and placement and diameter of perforations. If the concept had proved possible, considerable effort would have been required to provide a mass production capability with acceptable quality control.

5. The fuel displacement and weight penalties were greater than the goals of 4.5 volume percent and 2 lbs per cubic foot required for aircraft fuel system applications. These deviations probably could be corrected through improved manufacturing technology in providing a uniform wall thickness ranging from

0.008 to 0.010 inch. The test spheres also retained excessive fuel, which would be eliminated by more uniform distribution of the perforations. The results of fuel pumping tests indicated the perforated spheres would impose some aircraft performance degradation. As with the foam, small gross void areas would be required around fuel pumps, fuel gages, and tank vents.

6. An arrestor configuration with a geometry other than spherical could provide a random packing factor greater than 0.65, which would provide superior flame suppression performance. However, in view of the inferior performance of this concept under gunfire test conditions and the complexity of the manufacturing technology that would be required, this approach is not considered practical at this time.

7. The hollow plastic spheres did not provide any advantage in reducing the probability of external fire from incendiary projectiles in liquid fuel. Apparently, benefits experienced with whiffle golf balls were due to a check-valve type action, wherein the spheres blocked the projectile entry hole and delayed the fuel back-spurt. The need for small diameter spheres to suppress vapor-phase flames and explosions reduced this check-valve action. The entry hole made by a tumbled 50-caliber incendiary is approximately 1-1/2 inches in diameter, or about the size of a golf ball.

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G. W. Gandee,
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13. ABSTRACT

An investigation was conducted to establish the feasibility of using perforated hollow plastic spheres to pack aircraft fuel tanks to provide fire and explosion suppression capability. The program involved establishing several sphere configurations, producing test quantities, determining performance under electrical spark and incendiary gunfire conditions, and evaluating fuel system compatibility. Three sphere configurations varying in diameter from 3/4 to 1 inch with perforations of 0.060 to 0.100 mils were evaluated. All configurations provided some explosion suppression, but the goal of 3 psi maximum peak pressure rise required for fuel tank applications was not achieved. Fuel system compatibility was slightly inferior to that experienced with polyurethane foam. Spheres with optimum physical characteristics were not produced due to program restrictions. Studies indicated several potential production methods, although further development would be required.

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Aircraft Fuels						
Aircraft Vulnerability Reduction						
Thermoplastic Perforated Spheres						

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